Innovation in Weaving at ITMA 2019

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Introduction

ITMA 2019 (18th show) was held in Barcelona, Spain, June 20-26. In its press release from June 27, CEMATEX (the European Committee of Textile Machinery Manufacturers), the owner of ITMA and ITMA ASIA, reported that over 105,000 visitors from 137 countries and 1,717 exhibitors from 45 countries participated in the show. The show is marked as record-breaking in terms of number of exhibitors since its inception in 1951.

This ITMA is characterized by featuring innovative technologies, digital formation of fabrics and garments, digital printing, addressing sustainability concerns, formation of innovative products (such as e-textiles, 3D, and sportswear), and software (CAD for knitting and weaving, supply chain management, user-machine interface, etc.). While there is economic uncertainty due to trade dispute, exhibitors are pleased with seriousness of investors. Perhaps the announced highest investment is the plan for Egypt's textile industry to undergo a comprehensive modernization program valued at 1 billion Euro. The planned modernization includes machinery from major machine manufacturers (Benninger, Brückner, EFI Reggiani, Itema, Karl Mayer, Rieter, Savio and Thies) for fiber handling, spinning, knitting, weaving preparation, weaving, dyeing and finishing, and garment making. Nice Corporate Services, a Nigerian-based private company, is building vertically integrated textile manufacturing facility over 300 hectares that encompasses from ginning to finished fabrics. The project will reach its goal of producing 400,000 meter/day in various phases. The company signed a contract with Picanol for delivering various models of OminPlus-i air jet weaving machines that were exhibited at the show.

This paper deals with the innovation in weaving. As other stands, the weaving stands were well attended by visitors. Like previous shows, the major machine manufacturers demonstrated diversified machines for formation of woven products for apparel, home textiles, and technical textiles applications (Seyam 2008, 2012, innovative technologies were exhibited. Additionally, machine manufacturers marketed their technologies as industry 4.0 ready indication of readiness for the fourth industrial revolution that started in 2000. The industry 4.0 is taking advantage of electronics and computers of industry 3.0 era to create applications using robotic, internet of things (IoT), artificial intelligent, big data, etc. Just like industry 1.0, the textile industry has its sizable share of the industry 2.0 and 3.0.

This paper sheds the light on the features of improved and new innovative technologies and address the author's views on the opportunities and challenges that faces the weaving industry to advance toward industry 4.0, which is based on direct observations at nine ITMA shows, other shows, meeting with machine manufacturers and plant visits.

Warping, Sizing and Sample Weaving

To be competitive and meet the demand for new products' diversity, it is required to be equipped with rapid prototyping machines for sample production and evaluation prior to the main production. Using production warping, sizing and weaving machines to produce small samples leads to significant loss of production and material waste. Machine manufacturers offer solutions to avoid these drawbacks and developed warping, sizing, and weaving equipment dedicated for the production of samples and small runs. This section is devoted for the most innovative sample machines for warp preparation and weaving.

CCI Tech Inc., which is based in Taiwan**,** is specialized in manufacturing of sample warpers, sizing winders, and sample weaving machines. The company showed its new Lutan.com sample warping machine with creel integrated into the movable warping ring (Figure 1) to save space as compared to the previous Lutan v5.0 and v3.6 versions, which were shown at previous ITMA shows, which require stationary standalone creel with considerable space requirement. Lutan v5.0 and v3.6 features are reported elsewhere (Seyam 2016). The features of the Lutan.com include 2.6 m working width, 15-500 m warp length range, 14,400 m/min warping speed, 24 creel capacity, 5 m pattern drum circumference, and 10 lease rods. With these features, the machine is capable of producing intricate color sequence for narrow-wide sample and medium run production. The Lutan.com is equipped with built-in software (Lutronic and SE-edit) with user-friendly interface to enable setting the color sequence, number and locations of leases and other warp specifications. Following the user input, the machine automatically forms the warp with desired specifications per user input. However, the beaming events require the operator intervention to transfer the warp from the pattern drum to the warp beam.
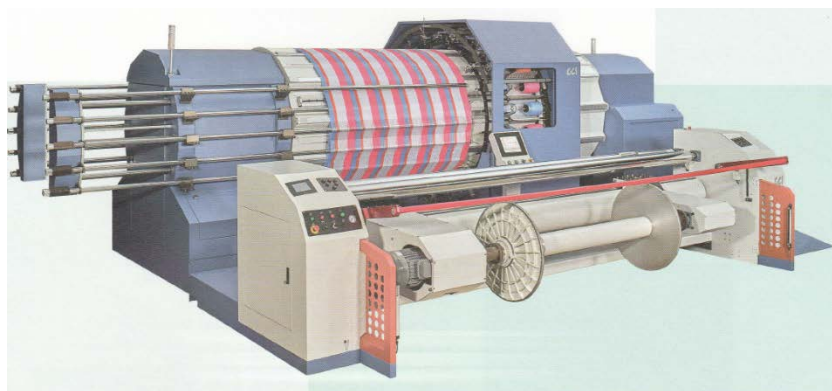

Figure 1. CCI's Lutan.com sample warper

To produce samples from yarns that require size treatment, sizing winders is the simplest route to provide sized yarn wound packages to sample warpers. In fact, there are companies that use sizing winders paired with sample warpers not only to produce samples but also to utilize for short, medium, and long runs. **CCI Tech Inc.** provides sizing winders. At this show, the company exhibited 2-spindle sizing winder Taroko. The machine is offered in 2-spindle and 4-spindle modular versions in maximum of 4 modules (i.e., maximum of 16 spindles). Each spindle (position) is individually controlled with dedicated driving system, size box and heating zone. With this setting, the machine can be used to run different yarns with different size formulas and size concentrations, size-wet-pickup (and hence size add-on), etc. The machine may run up to 500 m/min sizing speed. The Taroko is equipped with industrial PC/Windo OS and

internet access via WiFi/Ethernet for remote control and monitoring of each position.

CCI Tech Inc. also showed two of its single rapier sample weaving machines, evergreen II and Kebalan. The evergreen II has the same features as the previous version evergreen I but more compact to save space and much faster. The evergreen II is available in weaving width of 50 cm or 90 cm and can run up to 100 picks/min weaving speed. The Kebalan is still at its prototype stage. It is characterized by its high weaving speed of 300 picks/min, which is a record in sample weaving, shedding motion (8 or 16 harnesses) with individual harness control using servomotors, weft break detection and optional warp stop motion. The machine is equipped with 8 weft feeders to cope with the high speed weaving. The machines are provided with integrated controllers and CAD system for weave/pattern creation/entry with user-friendly interface.

Karl Mayer showed a version of their sample warper Multi-Matic®32. The 32 is the creel capacity (permitting the use of 32 different yarn colors). The company offers 3 versions of Multi-Matic® with creel capacity 32, 64, and 128 wound packages. The Multi-Matic® with creel capacity of 128 was shown at ITMA 2011 (Seyam 2012). The three versions provide flexibility in terms of creel capacity depending on the space and applications required by weavers. The comparison between the different versions of Multi-Matic® is shown in Table 1. As indicated in the table, the machines are capable of producing warp length range of 35-1,050 meters in case of 32 version and the range is higher (35-1,500 meters) in case of 64 and 128 versions. With such range of warp length and width, the machines are capable of producing narrow-wide short warps for sample weaving as well as wide and long warps for production weaving. Thus, the Multi-Matic® machines are directly competing with sectional warpers. Additionally, the machines are not limited in terms of color repeat size (the entire warp can be one color repeat, Figure 2) compared to the limited color repeat size in sectional warping machines. Beside the unlimited intricate color sequence, other features include automatic color change, short set up time of color sequence and desired number of leases via friendly user interface CAD system. Following the pre-programming and setting of the packages on the creel, the rest of the warping process is automatic, including the leasing for drawing-in and size rod separation. After the warping is completed, the beaming process requires the operator intervention to transfer the warp from the pattern drum to the warp beam.

Figure 2. Demonstration of color large repeat size in Multi-Matic®

Table 1. Comparison between features of Multi-Matic® warping machines

Parameter	Multi-Matic®64 and 128	Multi-Matic®32
Working (Warp) Width, m	3.6 and 2.25	2.25
Warp Length Range, m	35-1,500	35-1,050
Creel Capacity, max number of packages (colors)	64, 128	32
Optical Yarn Break Detection	yes	yes
Maximum Warping Speed (yarn speed), m/min	800	800
Maximum Color Change Speed, m/min	800	800
Maximum Beaming Speed, m/min	60 150 (optional)	60
Beaming Tension Range, N	370-4,500	600-4,500

VANDEWIELE unveiled a creel termed "Smart Creel". The creel is constructed with cells arranged in rows and columns (matrix) as it can be seen from Figure 3. The yarn is wound on each cell from large package supply through yarn feeder (same as weft feeder) by a robot. Different colored yarns needed for the carpet design are supplied from large packages. At the show, the Smart Creel was set behind VSi32 Velvet Smart Innovator equipped with Jacquard to feed the pile yarns. The length of warp pile yarn per each cell (bin) is preprogrammed according to the carpet design. Several creels and robots (Figure 4) may be used to accelerate the warping process. The Smart Creel provides several advantages. These include: (1) elimination of human error for color arrangement in the creel, (2) elimination of back winding of packages and the need for winders, (3) elimination of downtime for loading/reloading the creel, (4) reduction of waste due to its smaller size compared to traditional creel (bins are closer to the weaving machine) and (5) reduction of creel space since the bin's size is much smaller than a wound package. While the Smart Creel is intended for short runs (or samples) that may run back-to-back, the concept could be expanded for medium and long runs by increasing the size of cells (bins). The Smart Creel can replace traditional creel of sectional warper (indirect warper) and sample warper. The application of Smart Creel may be also expanded to direct warping for medium and large runs depending on the bins size.

Figure 3. VANDEWIELE's Smart Creel Robot winding a red yarn onto a cell (Source: https://www.vandewiele.be/en/activities/smart-creel, retrieved July 21, 2019)
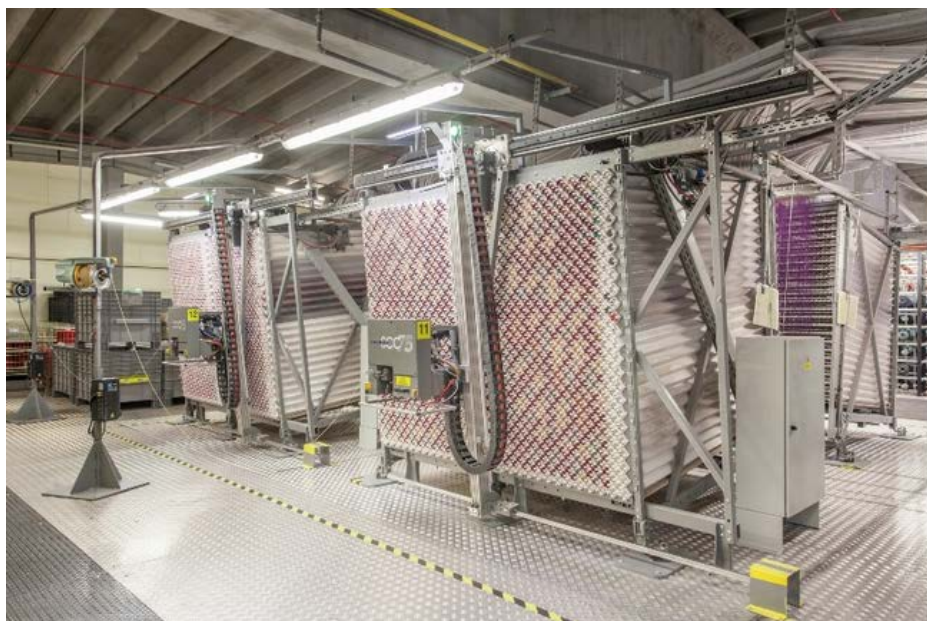
Figure 4. Smart Creel with multiple Robots (Source:
https://images.search.yahoo.com/yhs/search;_ylt=AwrCwOKgVzRdB3gApQEPxQt.;_ylu=X3oD
MTByMjB0aG5zBGNvbG8DYmYxBHBvcwMxBHZ0aWQDBHNlYwNzYw--
?p=smart+creel&fr=yhs-adk-adk_sbnt&hspart=adk&hsimp=yhs-adk_sbnt)

VANDEWIELE exhibited another creel termed "Fast Creel" that was set behind a new RCE2+ Rug and Carpet weaving machine to feed pile yarns. In the Fast Creel, each pile yarn is controlled individually by servomotor that regulates the feed and tension of each yarn according to the pile length needed per the carpet design (Figure 5). The servomotor is also functioning as a stop motion when its yarn is down via smart sensing of its torque. This allows the pile yarns to be fed directly to the machine without the need for passing through traditional stop motion a matter that save time and allow fast creeling of yarn packages.

Figure 5. VANDEWIELE's Fast Creel of rotating packages and servomotors

VANDEWIELE developed TEXconnect system associated with carpet weaving production that acquires data on each pile yarn consumption and tension and threading. The system also provides predictive maintenance. The combined development of Smart Creel, Fast Creel, and TEXconnect systems, self-learning carpet weaving machines is possible.

Tying-in and Drawing-in

Groz-Beckert exhibited new automatic drawing-in machine WarpMasterPlus, which is based on the previous version WarpMaster shown at ITMA 2015. WarpMasterPlus has the same features as the previous version plus additional features that include operation via a modern and swiveling computer with touchscreen (with optional 2 screens) for user convenient. As the previous version, the WarpMasterPlus draws warp from a single yarn package followed by tying-in process, then weaving.

Groz-Beckert continued to show its different versions of KnotMaster (AS/3, TS/3, XS/3Q, RS/3, RSD/3, 2s/3, and TS/3 TapeMaster) automatic tying-in machines for broad range of warp yarn types. These include yarns from natural and synthetic fibers, monofilament yarns, textured yarns, yarns containing spandex, steel wires, PP and PET tapes, fancy yarns, yarns from glass fiber and high performance yarns. The machines are capable of double end detection from leased or unleased warps and equipped with yarn break detection.

Staubli continued to exhibit its SAFIR 60 automatic drawing-in machine. The features and different types of SAFIR machines along with their applications are reported elsewhere (Seyam 2016). The company also showed a new tying-in machine TIEPRO. The most important feature of this machine is the new method of yarn separation. The traditional method of yarn separation is achieved with needle. Range of needles are required to handle separation in terms of yarn type and size. The

TIEPRO uses a small conical yarn separation mechanism and thus there is no need for needles.

Weaving

Dornier exhibited a total of five air jet (A1) and rapier (P2) weaving machines (three at their stand, one at Staubli stand and one at Bonas stand) weaving diverse range of fabrics for apparel, home textiles, and industrial textiles. Two P2 rapier machines, which was shown at ITMA 2015 before commercialization, were shown at this ITMA. P2 Type TKN 8/S G24/190 cm machine was weaving upholstery fabric and P2 Type TKN 4/E D8/360 cm was weaving coating fabric at filling insertion rate (FIR) of 925 and 1,134 m/min, respectively. The other three machines were A1 air jet. A1 Type AWS 6/S G16 / 210 cm was weaving automotive upholstery fabric at 2,010 FIR, A1 ServoTerry Type ATSF 8/JG / 340 cm was weaving Jacquard terry fabric at 2,184 FIR, and A1 Type AWS 6/JG / 240 cm was weaving Jacquard women's wear fabric at 2,147 FIR.

Itema Company showed six new (two air jet and four rapier) versions weaving machines A9500-2 and R9500-2 at one booth and at another booth Itematech (previously Panter that joint Itema recently) showed four repair machines; one is R9500-2, two Hercules, and one UniRap. The machines were weaving diversified products for apparel, home textile, and technical textile. At Itema booth, one of the air jet machines A9500-2/340 cm was weaving bed sheet and the other A9500-2/190 cm was weaving apparel fabric. The four rapier machines R9500-2/220 cm, R9500-2/190 cm, R9500-2/340 cm, R9500-2/260 cm were weaving denim, shirting, Jacquard upholstery, and Jacquard beach towel, respectively. The four machines at Itematech booth were weaving filter fabric (R9500-2/280 cm), geotextile (Hercules/550 cm), heavy filter fabric (Hercules/380 cm), and furnishing fabric (UniRap/160 cm). The UniRap (exhibited by Panter before joining Itema) machines are single positive rapier that were introduced at ITMA 2015 as prototype. At this ITMA, the UniRap/160 cm was weaving a furnishing fabric from warp and filling yarns made of linen (flax) fiber in a form of spread tow with zero twist. The linear density of warp and filling yarns was 1,000 tex and warp and filling density was 0.67 threads/cm. To keep the warp yarn orientation flat, a special heddle wires with flat eye were used. The weft feeder of rotating package was also used to keep the filling orientation flat without adding twist. This machine could be used to weave spread tows from high performance fibers such as Kevlar, Carbon, Zylon, etc. It should be noted that the warp was fed by creel holding the packages of the spread tows. This setting does not require warping process since the total number of tows is not high (0.67 threads/cm x 160 cm = 107).

Itema also introduced a new weaving machine model DISCOVERY, which was one of the main weaving attractions at the show, with new filling insertion mechanism. While the company referred to the weft insertion as "Positive Flying Shuttle", the machine is shuttleless that using stationary weft packages and filling yarn feeders that are characteristics of shuttleless weaving. Thus, the machine is a shuttleless projectile machine with gripper that is similar to the traditional Sulzer's projectile. Itema did not provide information other than two demos per day and a youtube video that was played from a monitor situated by the machine. While projectile is used as the filling insertion mean, its acceleration is conducted by drastically different mechanism. In the traditional Sulzer (part of Itema), the projectile acceleration is conducted by a picking arm that takes its motion from a torsional shaft. In the case of the DISCOVERY machine, as it can be seen from the youtube video, the projectile is accelerated by a bar (termed by author "picking bar") that moves horizontally in a groove. The bar contacts the projectile and moves it a certain distance to provide enough acceleration (energy), then reverses its motion leaving the projectile with the filling yarn to complete the insertion. The contact between the picking bar and the projectile over certain distance/time could be to provide

smoother motion with gradual acceleration rather than the sudden impact method in case of the traditional Sulzer's projectile. During its movement through the shed, the projectile is guided by tunnel with different and simpler shape than the traditional Sulzer projectile. Similar to the traditional projectile, the DISCOVERY machine has several projectiles and the insertion is performed from the left side of the machine. The machine was weaving two side-by-side denim fabrics with 8.75/1 cotton warp yarn, 20 ends/cm, 167x2 Dtex Polyester/Spandex weft yarn, 18 picks/cm, and 3.72 m width in reed. The DISCOVERY machine weaving speed was 350 picks/min or (1,302 m/min filling insertion rate) and it can run at 400 picks/min (or 1,488 m/min filling insertion rate). This is similar to the speed (or filling insertion rate) range of the traditional projectile machines. With limited available knowledge from Itema, full features and applications of the DISCOVERY machine are yet to be revealed and evaluated by weavers.

At its booth, **Picanol** Company of Belgium showed ten weaving machines. Five of these machines were air jet machines (two OmniPlus-i-4-D-190 one weaving a car seat fabric and the other a poplin fabric, OmniPlus-i-4-R-190 weaving a parachute fabric, OmniPlus-i-4-P-280 weaving a sheeting fabric and OmniPlus-i-4-P-190 weaving a bottom weight fabric). The other five machines were rapier machines (OptiMax-i-4-R-220 weaving a denim fabric, OptiMax-i-4-P-540 weaving an agro-textile fabric, OptiMax-i-12-J-190 weaving a Jacquard upholstery fabric, TerryMax-i-8-J-260 weaving a Jacquard terry towel and OptiMax-i-4-R-460 weaving a coating fabric). The range of the filling insertion rate of the air jet machines was 1,914-2,535 m/min and for the rapier machines, with the exception of the two machines weaving Jacquard terry and upholstery, was 1,456-1,485 m/min. TerryMax-i-8-J-260 and OptiMax-i-4-R-460 machines were running at variable speed depending on different terry parts and filling yarn types, respectively.

Picanol built the OptiMax-i weaving the denim fabric with near fully digitized filling insertion. The pre-winder (filling feeder) is equipped with programmable tension display (TED) with digital setting of the brake to control filling yarn tension during insertion. This permits storing and monitoring the ideal tension for a given filling yarn for reproducibility in the future. The machine is also equipped with Electronic Right Gripper Opener (ERGO) that is electronically controlled (instead of mechanical adjustment) to digitally set the gripper opening to minimize the length of the filling waste at the right selvage of the fabric. Additionally, the machine is furnished with QuickStep filling presenter that allows digitally programming different timings for filling presentation, insertion and rest. With these features along with already established digitized weaving efficiency and stop (warp, filling, and other stops) data acquisition, self-learning machine is possible if big data analysis and artificial intelligent can be added to get to industry 4.0.

Smit srl Company exhibited five machines. Four machines were shown at its stand and one machine at **VANDEWIELE** booth. The latter is model ONE (single rapier), with 190 cm reed width, free flight system (no guide is required to support the rapier during weft insertion) weaving intricate upholstery fabric at 380 picks/min (722 m/min FIR). Two model ONE machines were shown at ITMA 2015 and weaving upholstery and 2-way stripped apparel fabric. The other four machines were:

(a) New model GS980 with 360 cm reed width weaving Jacquard bed sheeting at 360 picks/min (1,296 m/min FIR) using Bonas jumbo Jacquard of capacity of 27,648 hooks; the highest exhibited at this show,

(b) Model GS980 machine with 220 cm reed width, weaving synthetic sportswear dobby fabric at 550 picks/min (1,200 m/min FIR) with new device termed 2SAVE that eliminates auxiliary selvages from both sides and allow the cut weft recycling.

(c) Model GS980 machine with 280 cm reed width, Jacquard Staubli 6144, weaving Jacquard Terry fabric at 289-320 picks/min (809-896 m/min FIR), and

(d) Model FAST weaving machine with 220 cm reed width, double free flight rapier producing denim fabric at 700 picks/min rpm (1,540 m/min FIR), which is high speed for free flight.

Toyota continued to show JAT 810 air jet machines that were shown at ITMA 2015. Three JAT810 machines were exhibited weaving at this show. These were JAT810 8T-280ES-ET weaving three side-by-side bath towels, JAT810 6SF-340DE-EF weaving curtain fabric, and JAT810 4F-190EC-EF machine forming upholstery fabric. Additionally, the company showed new machine introduced as "JAT New Concept" air jet weaving machine forming stretch bottom weight fabric of 230 cm width. The company indicated that this is their next generation air jet machine looking ahead of automation, smart factory and eco-technology.

Tsudakoma continued showing three ZAX9200i Master Air Jet Looms. The company showed one of these machines at the previous ITMA show (Seyam 2016). One of the machines was ZAX9200i-190-2C-C6 weaving industrial fabric from fine PE monofilament of 33 dtex in both directions (warp and weft) at 1,200 picks/min and width of 1.56 m (or 1,872 m/min FIR). Normally, water jet weaving is used for fine monofilament filling insertion. The second machine was ZAX9200i-190-4C-D16 weaving interior upholstery fabric at 1,300 picks/min and width of 1.707 m (or 2,219 m/min FIR). The third machine was ZAX9200i-Terry-280-8C-J weaving three-side-by-side Jacquard terry fabrics at 1,000 picks/min for terry sections and 750 picks/min for the boarder sections and width of 2.596 m (or 2,596 and 1,947 m/min FIR, respectively).

The show speeds and filling insertion rates did not vary much compared to previous ITMA shows confirming the fact that they reached the limit. As previous shows, the focus of the weaving machine manufacturers was on diversity of their products. With such variety of weaving machines, machine manufacturers demonstrated their machines' capabilities to weave for the three markets, namely, apparel, home textiles, and technical textiles (Seyam 2008, 2012, 2016).

Narrow Weaving for Smart Applications

At ITMA 2011 (Seyam 2012), **Jakob Müller**, demonstrated a new wireless smart label for antifraud identification using radio frequency (RF) technology. The smart label consists of a woven antenna from textile yarn and electrically conductive yarn and a chip with integrated circuit. The antenna and the chip are connected with thermoplastic adhesive. At this ITMA, the company showed a narrow weaving machine NFM®MDW® identified as "Multi Direction Weaving". The machine was weaving fabric containing two electrically conductive yarns from blend of PES/Cu/Ag (e-yarns). The two yarns were moving independently from the main shedding motion by the aid of guide for each. A strategic motion can be preprogrammed to raise electric yarns out of the reed (an open reed or comb), move to either side specified distance and picks, lower to interlace with weft yarn. The calculated movement of e-yarns' guides results in the formation of area covered with electrically conductive yarns distributed over the fabric surface with desired pattern. The Cu and Ag are anti-bacterial and electrically conductive materials and product with such elements may be used as shoe liner and heating. The fabric with electrically conductive circuit can be used to connect devices in electronic textile that have range of applications.

Three-Dimensional (3D) Weaving

Similar to previous ITMA, 3D weaving had its share. However, at this ITMA more companies contributed to the filed. At the last show, **Staubli** displayed 3D woven samples to demonstrate the capabilities of the company's Jacquard and dobby weaving machines. The display contains 3D orthogonal, 3D variable thickness, distance (spacer), stitched

multilayer, and unstitched/stitched double cloth for insertion of equipment (Figure 6). The applications of these samples include preforms for composites, soft/hard body armor, embedded electronic textiles, sensors, etc. In addition, at the last show **Vandewiele** reported in its Face Brochure 3D fabrics such as distance (spacer) and stitched/unstitched multilayer fabrics. Figure 7 shows applications of distance fabrics in boat and transportation applications taken from the Face Brochure. At ITMA 2019, **VUTS** (Liberec, Czech Republic) Company showed a new air jet weaving machine dedicated for weaving 3D distance fabric with constant or variable distance between the top and bottom base (ground) fabrics (Figure 8). Two warp beams were used; one to feed the warp sheet

for the top and bottom ground fabrics and the other to feed the pile warp sheet. The potential applications for the distance fabrics include inflatable boats of different type, dock, mats, flood protection, lifting bags, etc. Currently, the inflatable boat industry is using drop stitch technique to distance two fabrics that will be laminated post drop stitching. Numerous needles are used for joining the two base fabrics. The drop stitch machines and setting procedures are complex and lengthy. The process may take over 20 days to remove and replace the needles (http://www.nrs.com/tech_talk/dropstitch.asp). The distance fabrics produced by the weaving process are much faster (productive) and easier to design and form with desired geometry.

Distance (Spacer) Fabrics	Distance (Spacer) Fabrics	Stitched Multilayer Fabrics
Variable Thickness Multilayer Fabrics	Variable Thickness Multilayer Fabrics	Multilayer with Spaces for Insertion

Figure 6. 3D samples shown by Staubli at ITMA 2015

Transportation Applications

New 500 L Fiat Boat from Distance (Spacer) Fabric

Figure 7. Applications of 3D multilayer and distance fabrics produced by Jacquard weaving machines (Source: Van De Wiele's ITMA 2015 Face Brochure)

Optima 3D, new company formed in 2018, has designed and developed a range of 3D weaving machines for formation of preforms for the composite industry. The company showed its Optima 500/150, which uses shuttle system for weft insertion and a Jacquard shedding system with electronic user interface for structure parameters input that provide preforms design flexibility. While **Dornier** did not exhibit its new 3D

weaving machine that was announced few years ago, the Company provided brochure on their composite systems that included 3D weaving, which is used to manufacture multilayer preforms for composite applications. The features of the machine include the use of CAD system to program the weave structure, rigid rapier filling insertion system, individual warp yarn control Jacquard shedding system, creel for feeding warp yarns from wound packages, and an optional horizontal take-up system for thick preforms.
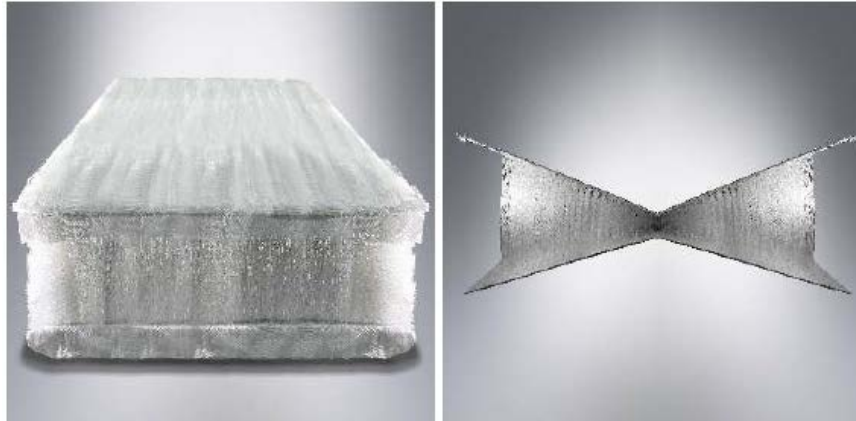

Figure 8. Constant and variable thickness distance fabrics produced by DIVA machine

(Source: VUTS brochure)

The multi-layer (3D) weaving techniques have been known for long time and used for the production of upholstery, hoses, tubular grafts, air bags, etc. using one shed at a time. These products were developed before the invention of CAD systems using mechanical dobby and Jacquard shedding systems. With the development of high-speed electronic dobby and Jacquard system, the CAD systems are must to create digital weaves to control the movement of warp yarns to form individual sheds according to weave design. While these CAD systems can be utilized to develop 3D orthogonal, cellular, I-shape, and T-shape structures, it requires very skilled woven designer with deep understanding of the 3D fabric geometries. The need for CAD systems that is intuitive and easy to use to develop 3D fabrics are sorely needed. The software company **EAT** recently developed the 3D Weave Composite Software. The warp or the weft cross-section is drawn digitally on square paper along with providing information on warp and weft yarn size and color (type) of each warp layer via user interface. Then the system provides colored 3D visualization of the structure. The software then converts the design to traditional up and down motion of each warp yarn to weave with one shed at a time weaving machine.

Industry 4.0 Readiness

No doubt that the weaving machine manufacturers benefited from Industry 3.0 and developed automated motions even in the 90s taking advantages of the development in electronic sensors, computers, and robotics. The last three decades witnessed the development of highly automated weaving machines that contributed to the reduction of defects, increase in productivity, and monitoring weaving room performance remotely. Table 2 depicts list of automation and their functions and limitations.

Table 2. Automated weaving motions/processes and their function and limitation

Motion or Process	Function	Limitation
Warping Process	Almost automated in sample and sectional warping with minimum labor intervention.	Beaming after warping requires operator intervention. It is not hard to fully automate the process including beaming using robots.
Drawing-in Process	Required when a new style need to be woven. After setting the drawing-in machine via user interface, automatic drawing-in of warp yarns is performed from a package or beam(s). Staubli's SAFIR recognizes yarn color and sequence of colored yarns is conducted automatically. Also, yarn twist, and double yarn are detected.	Setting, including placing heddle wires, drop wires, and reed, is manual. The draw according to weave design is also entered by operator.
Tying-in Process	Performed at the loom and used if the loom continues to weave same style. Knotting the corresponding yarns from the depleted warp sheet to the yarns of the new warp sheet is automated.	Operator is needed to prepare warp sheet prior to knotting (takes more time than the knotting itself). During tying-in process the weaving is stopped. New patented technology eliminate most of the stopping time and the weaving process continues during tying-in (Seyam and Oxenham 2018).
Quick Style Change	Special equipment to remove empty warp beam from loom along with harnesses, drop wires, reed and transfer the full warp beam along with harnesses, drop wires, and reed from drawing-in room and load them to the loom. Lead to significant reduction of style change time.	Requires operators and special weaving machine design. Could be automated using robotic system.
Weft breaks detection and repair	Using sensor to check whether the filling yarn arrived at the end of insertion time, automatically stop the process, remove defective weft yarn from shed using small robotic arms, and then restart the weaving.	Requires weaver's intervention to repair the break if it takes place before the main nozzle tip.
Warp breaks detection and repair	Currently, this is limited to stop if a wrap yarn breaks.	While there are several inventions, studies and trials, they are not commercially viable due to high cost
Pattern change	Electronic dobby and Jacquard (digital weaving) allowed changing the weave/pattern on the fly without stopping the process.	Use of the same warp. Operator is required to set filling feeders with the required yarns in advance

		of pattern change, however, this can be automated.
Filling selection motion	Allows preprograming of weft yarn sequence for the production of hybrid structures and width-way stripped fabric	
Variable weaving speed	Allows preprogramming weaving speed for each weft yarn	Operator has to find optimum speed for each filling yarn.
Variable pick density	Pick density can be preprogrammed in desired sequence for technical reason or fancy effect.	
Adaptive control system (air jet)	Sensing arrival time of weft yarn to prevent early/late arrival and avoid weaving defects. The adaptive control system may change the timing of opening the main nozzle valve and the magnet pin, changing air flow, or weaving speed (if the yarns can withstand increase in the speed)	
Monitoring weaving stops and efficiency	Weaving machines are interfaced to computerized data collection to monitor warp stops (from warp stop sensor), filling stops (from filling stop sensor) and other stops. Individual machine and weaving room performance can be monitored remotely.	Reason for stops are not known. Full advantages of the data are not utilized. IoT could be utilized through looking at the data by machine manufacturer and use AI and big data analytics to diagnose the reason for break, which could be due to machine performance, yarns' performance and/or environmental condition (Temp and RH). The stop data, wrap and weft yarn tension data, loom timing data, etc. need to be considered.
On-loom fabric inspection	A system that inspects the fabric quality and identify minor and major defects to enable rectifying the source of defect before substantial fabric is woven with target to produce high quality fabric.	Need to look at image recognition using AI and big data analytic to make decision on stopping the process for real fabric quality issues that must be rectified.

Additional technologies have been developed to enhance the fabric quality and increase intricacy of fabric design in dobby and jacquard weaving. These include separate drive of dobby/ Jacquard shedding motion (main motors drives all other motions), individual warp yarn control in Jacquard, individual harness control in dobby, direct drive (powerful motors). Details on the benefits and operation of these

technologies are explained in details in (Seyam 2008, 2012, 2016). Weaving machine manufacturers are also responding to the demand for sustainability by reducing power consumption and reduce warp and weft waste.

Road to Industry 4.0

Although the weaving machine manufacturers made progress toward manufacturing digital machines that are ready for industry 4.0, there are more that need to be done. Weavers are looking for weaving machines with automatic repair of warp breaks, fully automated start mark prevention mechanism that does not need operator intervention (requires vision system), fully automated style change, automatic formation of flexible integrated circuit (smart e-textiles), multiphase weaving machine for dobby and Jacquard weaving, and variable width/warp density Jacquard weaving to overcome the speed limit of single-phase weaving machine.

Plus eliminating the limitation mentioned in Table 2 and development of additional technologies listed above, the road to industry 4.0 requires systems to collect big digital data and store such big data (e.g., using cloud), use of IoT to allow machine manufacturers to access and process big data

using AI and analytics to diagnose and predict disruptive issues, development of robotics to complete automation, etc. It should be pointed out that the upstream (yarn manufacturing) and downstream (fabric finishing, conversion to products, and marketing) should be integrated with weaving since all data are correlated starting from fiber and ending with market. One major issue that manufacturers are concerned about is the compromise of their data and intellectual property (IP), which is an impediment to the road to industry 4.0. The textile is a global and diversified industry and there is a need for global laws to protect manufacturers' data and IP from hackers.

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